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Art. XV.—*The Sand Dunes of the Portland District and their Relation to Post-Pliocene Uplift.*

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Contents.

Introduction.

The dune areas of south-western Victoria afford convincing evidence of uplift of the order of 400 feet. The movement began after the Upper Pliocene, and has continued throughout the Quaternary, the most recent elevation being about 10 feet. The dunes comprise both recent and ancient (" fossil ") members, and are located in two main areas, viz., the valley of the Lower Glenelg River, and the coastal strip east of Portland. Much of the basaltic Portland promontory is capped by dune sands.

The country has a marked W.N.W. to E.S.E. trend, due chiefly to the coastline between Cape Bridgewater and the mouth of the Glenelg having this direction, but emphasized by the numerous transverse sand dunes parallel to the coast, by the great westerly bend in the Glenelg, by the Wanwin and Swan Lake faults, and by three lines of volcanic foci. In many respects the area can be regarded as a continuation, on a lesser scale, of the " Coorong " area, of alternate dune ridge and swale, which is the dominant feature (Fenner, 1930) of coastal south-eastern South Australia.

Nature and Extent of the Dune Formations.

The lower Glenelg dune-complex is 40 miles wide along Discovery Bay, and extends 25 miles inland. The bare shifting dunes of the two-mile-wide coastal strip gives place inland to older dunes fixed by vegetation, and their amplitude diminishes until north of Dartmoor they flatten out to a sandy plain at an altitude of 200 feet. In this sector the highest altitude attained is 250 feet, and the greatest amplitude of the dunes is about 100 feet.

On the eastern edge of the Glenelg basin, in Kentbruck and Balrook, the dune sands overlie basalt flows and attain altitudes varying between 400 and 500 feet. Similar conditions prevail throughout the Portland promontory, the dune formations ranging in altitude from 50 feet to 400 feet, according to the height of the underlying volcanic rocks, with two exceptionally high points at Mount Kincaid, where sands reach 500 feet, and Mount Richmond, capped by sands at 740 feet.

The dune ridges fringing Portland seldom exceed 100 feet in altitude, and the hinterland east of Mount Clay is a sandy plain, with underlying Tertiary limestone.

Attention is thus drawn to the range in age of the dune formations; it is apparent that the higher level sands of Portland promontory are older than the low-level ridges of Portland Bay, and that the innermost ridges near Dartmoor are older than the bare dunes of Discovery Bay.

The general orientation of the dune ridges is parallel to the coast, which runs roughly N.W.–S.E., and since the prevailing wind is south-westerly, the dunes are transverse ridges. Usually a foredune marks the shoreline, but in the Discovery Bay area, between Bridgewater Lakes and Swan Lake, there is an unusual arrangement of parallel dunes whose direction is oblique to the coast, being west–east rather than N.W.–S.E. No foredune is found in this stretch. The feature seems to be due to the merging of individual crescentic or sub-triangular dunes, whose leeward slopes originally ran N.S. and W.E. to form ridges in which the north–south slopes were obliterated, and the west–east slopes became pronounced. The commonest form (Pl. XIII., fig. 1) is the long irregular, sharp-crested ridge, with the windward side sloping at 10 to 15 degrees, and the leeward at 33 degrees maximum. However, there is endless variety in the size and shape of the dunes, and at either end of a crescentic dune the directions of the steep slopes may seem abnormal, e.g., if the main axis of the dune runs N.W.–S.E., the northerly end may curve round to run west, and at that point the steep leeward slope is towards the north; similarly at the southern end the steep slope may be to the south. But when the whole dune is considered, the dominant steep slope is to the north-east or east.

Wandering dunes, due to the merging of several dune ridges, attain considerable size. They possess flat or only slightly rounded tops, and steep sides sloping in several directions, e.g., north, east, and south. The altitudes may attain 220 feet, but they are composed of several individual dunes, none of which separately would exceed 100 feet amplitude. In no dune was there seen a steep slope to the west or south-west.

Destruction of previously built dunes by wind erosion leaves residual hummocks, fixed by rushes, marram grass, or ti-tree, standing 20 or 30 feet above the general sand-level. These

residuals are common in the coastal strip along Discovery Bay. Residuals of older dunes can be found in many of the wind hollows and in places along the beach, where the consolidated rock, dune-sandstone, or dune-limestone, crops out. Old soil beds are also exposed in places.

That the process of consolidation by compaction and induration begins soon after a dune is built may be observed in many places in the lower Glenelg area. After a spell of heavy rain followed by dry conditions, large flakes and sheets of partly consolidated sandstone may be found in the wind-hollows and troughs of the ridges. These are not portions of residuals, but newly-formed rock. Sometimes they disintegrate, especially those on the surface, but within the dune they are permanent, and form definite bedding planes.

The shores of Bridgewater Bay and Portland Bay are skirted by continuous foredunes, about 20 to 50 feet high and 100 yards wide, and partly fixed by marram grass, rushes, and other plants. A swale or interridge depression from 300 to 800 yards wide separates the foredune from the first dune ridge, which has a core of consolidated dune-rock, whereas the foredune is very largely composed of incoherent sand.

The Narrawong Ridge (fig. 1), which runs at an altitude of 50 feet from Narrawong to Yambuk, is a true dune ridge as defined by Johnson (1919), viz., a beach ridge overlain by aeolian sand. The beach ridge is now at about 20 feet altitude; it

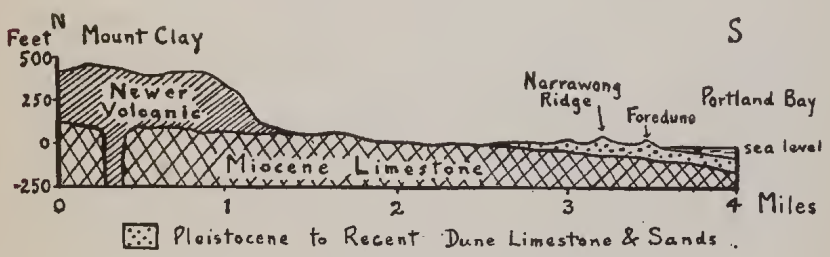

Fig. 1.—Section from Mt. Clay to Portland Bay.

contains abundant shells of species now living on the coast (see appendix) in a bed perhaps 2 feet thick. On either side of the main Narrawong Ridge are parallel raised beach ridges not capped by sand; in addition to their shells, they contain small rounded basalt pebbles. In allotments 4, 5, and 6, Narrawong, these pebbles attain 6-in. diameter, but elsewhere they are about 1 inch.

Between the Narrawong Ridge and the volcanic massif of Mount Clay there is a strip, about three-quarters of a mile wide, of Miocene limestone, with *Ditrupa, Lovenia,* &c. This is exposed

in many places, and is quarried in allotments 47 and 48, Narrawong. East of Darlot's Creek it appears in Castlemaddie P.R. and further east, gradually descending beneath younger sands in the Bessiebelle district.

Considerable progradation of Henty Beach, Portland, can be attributed to the construction of training walls and a breakwater at the mouth of Wattle Creek, causing deposition of silt from the creek and sand brought by long-shore currents from the cliffs. In this manner a width of 4 chains has been reclaimed from the sea within the century of settlement.

A two-mile-wide sand plain stretches from Mount Richmond to Portland South. It is best developed in the Cashmore Heath district, where extensive drainage works to the Wattle Creek were constructed by the Public Works Department in 1916. This plain lies between the basaltic plateau of Gorae and the dunes of Bridgewater, and probably represents the initial sand plain left when the seabed emerged, though the presence of certain inliers of dune limestone, such as Limestone Hill at Cashmore, suggests that denudation has also been effective in reducing the dunes to a fluviatile plain.

About two miles east of the mouth of the Glenelg, in allotment 15A, Glenelg, and at the western end of the Long Swamp, there is a "rake" structure due to the attachment of five or six subsidiary dunes at an angle of 45 degrees to the direction of the main foredune. The effect has been to divide the Long Swamp into a chain of swamps.

Along Discovery Bay is a chain of swamps and lakes, viz., Long Swamp, Bulley Lake, Lake Mombeong (Bong Bong), Malseed's Lake, Swan Lake, and Bridgewater Lakes, which according to some opinions form the remnants of an abandoned course of the Glenelg River. There is no geological evidence, in the shape of old valleys, pebble beds, river cliffs, or the like, that this is so; the swamps are true dune lakes or basins of internal drainage in the swales.

Details regarding the altitude and directions of many of the dune ridges are given on the geological parish plans published by the Geological Survey of Victoria. These include Glenelg, Warrain, Kentbruck, Balrook, Drik Drik, Kinkella, Wanwin, Palpara, Mumbannar, Dartmoor, Watacpoolan, Myaring, Killara, Werrikoo, and Wilkin, but do not cover the area east of the Glenelg Basin. A geological map by Reid (1932, Plate V.), published in Hamilton by Western Petroleum Ltd., covers the area around Portland, and a small area near Heywood was mapped by Kenny (1939). The portions not mapped in detail were sketched in by personal observation extending over three

years, but are subject to correction, particularly in the matter of surface sand. In many places a thin drift of sand masks volcanic rocks, and has been omitted; in others it is several feet in thickness and has been regarded as a definite formation. The accompanying map does not attempt to distinguish between Pleistocene and Recent sands and dune-limestone, though this is done on the parish plans of the Geological Survey.

Types of Sand and Dune-Rock.

All the sands except the most superficial are highly calcareous; the beach sands of Discovery Bay contain 75 per cent. of $CaCO_3$ and the finer sands of Portland Bay contain up to 93 per cent. $CaCO_3$. All are shell-sands derived from skeletons of marine molluscs and echinoderms, finely comminuted, with microzoa such as foraminifera and bryozoa. Where cliffs of Miocene limestone occur, as at Portland, the beach sands are more calcareous than those of the open coast, owing to the additional matter derived from erosion of the limestone. Complete shells are rare on the open beach, but in certain "Shelly Beaches" there are accumulations of pelecypods such as *Notocallista* in commercial quantities. All of the specimens collected, whether from loose sand, old soil beds, or consolidated dune-rock, are similar (see appendix) to species now living in Bass Strait, and may be of any age from Pleistocene to Recent. Identifications were kindly made by Mr. W. J. Parr (foraminifera), Mr. F. Chapman (land shells), Miss I. Crespin (shelly fossils), and the National Museum, Melbourne.

Mechanical analyses (see appendix) of sands were made at the State Laboratories under the direction of Mr. W. R. Jewell. They record the extreme fineness of the dune sands and of many of the beach sands, and indicate the efficient wind-sorting that took place during dune-building.

Chemical investigation was limited to estimations of $CaCO_3$, the method being to boil a weighed sample of sand with HCl. The purity of the sands enabled clay and humus to be ignored. No heavy minerals were observed in any of the sands; the residual grains after digestion with acid were invariably quartz, very fine, even-sized, and clear.

Five types of sand were established, though the differences between them are rather slight:

1. (*a*) Ocean Beach Sand.

Is typified by the creamy-yellow sands of the beaches of Discovery Bay. It consists of fragments of molluscan shells, coarse near the water's edge but finer up the beach, with spines

of echinoids, and microzoa. Fine quartz grains may amount to 20 per cent. of the total. 57 per cent. of the sand passes through 80 mesh but is caught on 100 mesh.

1. (*b*) Dune Sands Derived from Ocean Beaches.

These constitute the unconsolidated dunes inland from the beach of Discovery Bay. They are similar in all respects to the beach sands but are more uniform in grain-size and the particles are more rounded.

2. (*a*) Portland Bay Beach Sands.

Typified by the very fine specked grey-white sands of Henty Beach, Dutton Beach, Nelson Bay, Narrawong, and Tyrendarra. It consists almost entirely of shelly matter, 93 to 98 per cent. $CaCO_3$, and over 50 per cent. of the grains are between 60 and 80 mesh. Recent tetractinellid sponge spicules are common, and distinguish this type.

2. (*b*) Portland Bay Dune Sands.

Similar to the 2(*a*) type, except that the sponge spicules are almost absent. They merge into less calcareous ocean beach sands east of Yambuk.

3. Old Sandy Soils.

Old soil beds are intercalated between the courses of dune limestone. They are often reddish-brown but sometimes almost black, and are seldom more than 1 foot thick. The small land snail *Charopa* is characteristic of the lower soil beds. In the uppermost sand bed capping the cliffs of the Portland promontory there are many shells of the large land snail *Rhytida* and less abundant *Succinea*. Identifications are given in the appendix. $CaCO_3$ content is about 50 per cent., and grain size coarser than the dune sands, mostly between 40 and 80 mesh, and very well sorted. In this type may be included the brecciated old soils, consisting of fragments of old dune-rock and soils, intercalated between normal beds of dune-limestone.

4. Siliceous Sands.

The upper layers of nearly all the dune sands, particularly those that have been fixed for some time, are strongly leached, leaving almost pure quartz, but the percentage of lime increases with depth. Leaching is most pronounced in the swamps and depressions. The thin sandy cappings on the basalt flows usually consists of very fine quartz grains. Such cappings are found on the Kangaroo Range in Balrook and Drik Drik, and on Mount Clay and Mount Kincaid; they probably represent dune sands that have drifted and been leached.

5. Dune Limestone.

Some of the dune-rock has suffered leaching, and is now a friable sandstone; more commonly the hardness has been increased by induration, resulting in travertine which sometimes attains flint-like hardness. However, all the rocks are calcareous and may be included under the name limestone; $CaCO_3$ ranges from 50 to 99 per cent. The rock was derived from pure shell-sand.

In the Werrikooian (?) flaggy limestone at Dartmoor there is a proportion of flakes of white mica, but none is found in the dune limestones.

Structures in the Dunes.

Most of the unconsolidated sand ridges are asymmetrical, with leeward slopes steeper than the windward. The maximum slope does not exceed 33 degrees, which agrees with the measurements recorded by Etheridge (1876), Cornish (1897), Beadnell (1910), Shotton (1937), and Bagnold (1938). Actually, this angle was only rarely obtained where fine dry sand was on the verge of slipping; in most cases the angle of rest was 32 degrees. The windward slopes averaged 7 degrees for long distances, but in the crescentic dunes steeper angles occurred at the curved ends, angles of 25 degrees being obtained on both sides. None of the dunes measured had a steep face longer than 2 chains, though the windward face might be 15 or more chains long.

Some of the arcuate dunes simulate barchans but lack the characteristic horns on the leeward side. Usually individual dunes are somewhat crescentic or sub-triangular in shape. The long ridges have serrated summits, often with curious miniature wind troughs at the very summit, carving it into innumerable small grooves at right angles to its length.

The internal structure of the newly-formed dunes is only partly revealed in the wind-hollows; stratification and incipient compaction are readily noted, particularly in the gently sloping windward beds (Pl. XIII., fig. 2). In the old consolidated dunes, however, admirable exposures in the cliffs enable the rock-courses of dune-limestone to be thoroughly examined. Thus it is possible to work out the windward and leeward slopes of the ancient dunes, using the criterion of Shotton (1937) that dips of 25 to 33 degrees represent leeward slopes, and those less than 25 degrees represent windward slopes. This idea was applied by Shotton and the Lapworth Club to the outcrops and exposures of Bunter (Triassic) sandstone in Shropshire and Worcestershire and revealed that the structures were really ancient barchans built by a prevailing east wind. Applying this method to the outcrops of old dune limestone in the Portland District, the

directions of the steepest dips (rarely more than 28 degrees) were plotted wherever possible, and found to run mainly north-east, with some east and north. Thus they are similar to the modern dunes in having been built up by south-westerly winds.

Terminology for the windward and leeward slopes appears to need standardization: Shotton (p. 542) refers to leeward slopes as "deposition planes" and windward slopes as "planes of erosion", while Bagnold (p. 403) calls leeward slopes "encroachment planes" and windward slopes "planes of accretion".

Occasionally the cliff sections reveal what is apparently the crest of an old dune, resembling the axis of an asymmetrical anticline. An example of this occurs in the cliff above the landslip near the Flat Rocks at Kappa Camp, Nelson Bay. This is probably the feature described by Dennant (1887, p. 227) as a dome with quaquaversal dip, a term the suitability of which was disputed by Griffiths (1887, p. 72).

Minor features in the dune formations, especially where wind erosion has been active, are the "fossil trees", usually several inches in diameter but at times about 18 inches across, with hollow cores. They are due to incrustation about roots of ti-tree, &c., or in the larger "palmetto stumps" (cf. Sayles, 1931) possibly to incrustation around the bases of grass tree (Xanthorrea). Another feature is the miniature karst or irregular-surfaced travertine exposed on the west sides of the cliffs where wind erosion has removed 5 or 6 feet of soil.

After rain, it is interesting to note the leeward growth of the free dunes by the encroachment of dry sand over the moist firm sand on the steep side (Pl. XIII., fig. 3). Vegetation becomes covered by the moving sand and dies; the dead limbs are later exposed in troughs or wind-hollows as the dune migrates. No data are available on the rate of annual migration of the Portland dunes. The water table stands relatively high throughout the area, and the moisture content of the dunes is considerable. Consequently it is in the troughs and depressions that vegetation first gets a hold, usually rushes and grasses followed by ti-tree and larger plants, as described by Audas (1917), Patton (1934), and Cockayne (1911), leading to the ultimate fixation of the dune.

Solution by underground waters is responsible for the formation of numerous small caves, such as those in Batt's Ridges and the Bridgewater district, and at Puralka. In other places there are deep sink-holes (runaway holes), e.g., a sink-hole possibly 200 feet deep at Old Shelly Beach, Cape Nelson. Springs and seepages are common in the deeper valleys and on the coastal cliffs where the water table is intersected; at these points of emergence stalactitic growths are common.

Relation of Dune Formations to other Rocks.

The geological succession in the district is:—

RECENT alluvium, beach sand, dune sand, dune limestone (incipient), shell beds, shingle.

HOLOCENE basalt (Fitzroy River).

PLEISTOCENE dune limestone, shell beds, raised beaches.

LOWER PLEISTOCENE to UPPER PLIOCENE basalt, diatomaceous earth.

PLIOCENE oyster bed, shell beds, flaggy limestone.

MIOCENE marine limestone.

JURASSIC felspathic sandstone and mudstone.

Jurassic sandstone and mudstone outcrop in the Merino district, north of the area investigated, and exposures in the Portland district are limited to two small patches in the banks of the Glenelg and its tributary Stokes River, above Dartmoor. Borings reveal that they underlie the Tertiary limestone at Dartmoor and Mumbannar, and they probably extend south towards Portland, though at a great depth as the Portland bore did not bottom the Tertiary limestone at 2,265 feet. The dune limestone overlies the Jurassic, with or without the intervention of Miocene limestone.

The Miocene limestone is almost universal underground in the southern portion of the area, and outcrops in high spots at Heywood (Kenny, 1939), south of Mount Clay, and near the border at Nelson, as well as being exposed almost continuously along the banks of the Glenelg River, and in the sea cliffs of Whaler's Bluff and Double Corner at Portland. Wherever they come in contact, the dune limestone overlies the Miocene limestone unconformably.

Some difficulty exists with the subdivision of the Pliocene rocks of the area, owing to insufficient palaeontological work. Until recently, the oyster bed and associated shell beds of the Portland cliffs were doubtfully assigned to the Werrikooian (Upper Pliocene), but Miss I. Crespin, Commonwealth Palaeontologist, has classed a collection sent to her by the author as Kalimnan (Lower Pliocene). Details are given in the appendix. The fossils were collected from a road cutting in the face of the cliff near Double Corner, close to "Maretimo" homestead. Dune limestone does not come into contact with this formation.

Apparently the Werrikooian beds are restricted to the valley of the Glenelg. The type area occurs at the junction of Limestone Creek with the Glenelg, north of Dartmoor. There appear to be three beds, viz., upper: flaggy limestone; middle: Oyster bed (Ostrea limestone); lower: shell beds, which are the actual Werrikooian strata. There is probably not much difference in age between the (?) Werrikooian flaggy limestone and the oldest dune formations. After the Werrikooian beds were deposited in the estuary of the Glenelg, the post-Werrikooian uplift brought

these beds into a position suitable for the building of the first dunes, probably in the early Pleistocene period. Possibly the flaggy limestone is part of the first aeolian deposits.

In regard to the relationship of the Newer Volcanic Series to the dune limestone, it must be recognized, as pointed out by Hills (1939, p. 130), that the Fitzroy River basalt is much younger than the other volcanic rocks of the district. In the Tyrendarra Stoney Rises the basalt fills a valley eroded in dune limestone and raised beach ridges associated with the Narrawong Ridge. Inliers of the dune rock and raised shell beds were found in allotment 7B, Homerton, Section B, part of Narrawong, at 25 feet altitude. The locality is shown on Sheet 1 (Helio) of the Fitzroy River Survey made by the State Rivers and Waters Commission in 1933-34. The basalt extends a little east of Wright's Bridge, allotment 56, Narrawong, and according to fishermen it forms a submarine bank trending south-west for some miles in Portland Bay, off Tyrendarra. This basalt is therefore younger than the dune limestone, and is Holocene in age.

The majority of the Newer Volcanic rocks west of Portland are older than the dune limestone since they underlie the dune formations. Their ages may therefore range from Pliocene to Lower Pleistocene. The basal portions of the dune rock often contain embedded pebbles of basalt; these occur in the cliffs of Cape Grant, Cape Nelson, and Cape Bridgewater. Nowhere is there evidence of intrusive basalt in the dune rock, though some earlier observers have stated this, mistaking yellow tuff beds for dune limestone. It should be pointed out that access to the cliffs and shore platforms is easier now than hitherto.

The age of the basalt of the Kangaroo Range at Drik Drik and Balrook has caused considerable discussion, initiated by the different interpretations of the geology by Keble, who mapped the Drik Drik sheet, and J. Foster, who mapped Balrook parish. Keble regards the scarp of the Kangaroo Range as due to erosion by the pre-Werrikooian Glenelg River, thus making the basalts pre-Werrikooian in age. This interpretation was adopted by Sussmilch (1937). Evidence in favour of some antiquity for this basalt is that it carries a heavy forest of Messmate (*Eucalyptus obliqua*) in a deep red soil, with Brown Stringybark (*E. capitellata*) in the sandy patches. J. Foster discovered an important sink-hole in allotment 35, Balrook, which is 80 feet deep. On the east face there is Tertiary limestone capped further up the hillside by the Kangaroo Range basalt; on the west side there is an upper bed of dune limestone about 30 feet thick, resting at an angle of 30 degrees on a red-brown bed consisting of fragments of basalt and scoria set in red ash and clay. Foster regards this lower bed as a fault breccia, but it possesses many of the features of ejectamenta. Scoriaceous basalt 70 feet thick is exposed in the east bank of the Glenelg,

in allotment 3A, Balrook, about 1 mile from the sink-hole, and also on the opposite bank in the parish of Kinkella. Thus the basalt may be at the lower level for a reason other than faulting. The vents from which the main Drik Drik basalt flow was extruded are the twin hills, Mount Vandyke (Good Hill) and Mount Deception, in the parish of Cobboboonee. The rock is a holocrystalline andesine basalt with large white felspars and prominent olivines, similar in many respects to the Pirron Yallock type (Skeats and James, 1937) from the Stony Rises near Colac. By analogy it might be Holocene or Recent in age, but the stratigraphical evidence is at present very incomplete. There is no known bed of Werrikooian between the basalt and the Miocene limestone. Thin cappings of siliceous sands, probably drifted and leached dune sands, occur on the western margins of the basalt. It appears probable that the Drik Drik basalt is pre-dune limestone, and if the fault be admitted, possibly post-Werrikooian.

Basalt is brought into relation with dune limestone along a fault scarp, not previously described, which runs from Swan Lake to near Cape Bridgewater, and has caused a 200-ft. throw to the south. The old dune limestone has been displaced by this amount at the waterfall on Johnstone's Creek above Swan Lake. On the down-throw side the dune rock is exposed at intervals along the coast and in some of the depressions between more recent dunes in the sunkland. The below-sea-level beds of some of the Bridgewater Lakes may be attributed to this fault.

Evidence of Uplift of the Area.

General Uplift.

The pre-Newer Volcanic terrain was an immaturely dissected raised plain of Miocene limestone with relatively high points at Heywood, Condah, Narrawong, and Portland, and a wide bay where the lower Glenelg basin now exists. The coastline was further inland than at present, though its exact position is indefinite. In Lower Pleistocene times, or even earlier, the volcanic eruptions began at numerous vents along three main lines, viz., the northern, including Mt. Eccles, Mt. Eckersley, Mt. Deception, Mt. Vandyke, and vents near the junction of Moleside Creek with the Glenelg; the central, less defined, includes Mt. Kincaid, Mt. Richmond, and Mt. Clay; and the southern comprises Cape Bridgewater, Cape Nelson, Cape Grant, Lawrence Rocks, and Julia Percy Island. Possibly the southerly line of vents was submarine. Much of the extruded matter is tuff, which forms beds nearly 200 feet thick at Yellow Bluff, Cape Nelson, and over 100 feet thick at Cape Bridgewater, Cape Grant, and Lawrence Rocks. As far as is known, there is no evidence of fossils in the tuff, and the massive lava shows no spilitic characters.

The highest point in the district is Mt. Richmond, which is capped by dune sand at 740 feet. The sand is arranged in three tiers or arcuate dunes on the southern and western sides, each tier being about 100 feet high, bringing the base to the same level (400 feet) as the main plateau of the Bridgewater dune rock. The possibility of migration of sand dunes up the sloping sides of Mt. Richmond to form the three high level dunes must be considered. When the general level was 400 feet lower, the volcanic dome of Mt. Richmond would still have projected 340 feet above sea level, and dune sands may have been carried to that height provided that the slope was suitable. It so happens that the sides are very gently sloping, the mount being a large dome covering 4 square miles (see Fig. 2). Migration of dunes up considerable slopes is considered by Hills (personal communication) to have occurred at Cape Otway and Cape Schanck. It is suggested as the cause of the exceptionally high sands on Mt. Richmond.

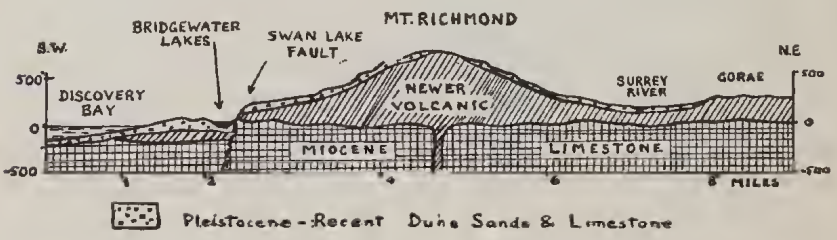

Fig. 2.—Section through Mt. Richmond to show high-level dune sands.

The widespread dune formations at 400 to 500 feet altitude, which cover the basaltic Portland promontory and its westward extension to Swan Lake and Mt. Kincaid, indicate uplift of the order of 400 feet, after allowing 100 feet as the height to which dune formations can be built and levelled off in this district. When the land was 400 feet lower all but the higher volcanoes were submerged. Probably Mt. Richmond (740 feet), Mt. Kincaid (664 feet), Cape Bridgewater (449 feet), and Mt. Clay (622 feet) had their summits above water. As uplift began, marine and acolian sands were deposited on the shores of these islands at successively lower levels. Thus the higher deposits on the eminences are the older.

When the uplift had proceeded until the plateau of basalt flows was about to emerge, dune building became much more extensive, resulting in the widespread deposits now forming the innermost old dunes. Uplift may not have been continuous owing to the eustatic rise and fall of sea level consequent on release and withdrawal of sea water during the interglacial and glacial epochs of the Pleistocene. Sayles (1931) has pointed out how this affected dune building in the Bermudas, and Hills (1939) has

suggested that similar conditions prevailed in Victoria. Glacial conditions reduced the level of the oceans and accelerated the building of dunes, but interglacial conditions caused a rise of sea level, inhibiting the growth of dunes, which became fixed by vegetation and developed soil beds. In the Portland district a total of five beds (some soil beds and some brecciated-sandstone beds) has been developed, which agrees with the suggestion of Hills that this may be the maximum number in the Victorian dune series.

With continued uplift, the higher dunes became stranded, others being formed further out on the receding shoreline. Not every dune ridge is a stranded foredune, as several ridges were formed at the one sea level, and would be stranded as a group. Wind planation and occasional marine transgressions reduced the summits of these dunes, making a platform of dune rock with fairly level top. Upon this, during interglacial periods, further generations, possibly two or three, of dune rock might develop, separated by the erosion planes and possibly by old soil beds. The complete sequence of dune formations could never be formed in any one place; usually the thickness of dune rock at one place does not exceed 100 feet; the maximum on the coastal cliffs is about 150 feet near Kappa Camp, Nelson Bay.

When the basaltic plateau had fully emerged, the bay which is now the basin of the lower Glenelg had become defined, and so had Portland Bay. During this uplift the formation of shallow water marine sediments in the Glenelg basin occurred, i.e., in Pliocene (probably Werrikooian) times, and was followed by dune building, which is still proceeding. The dune building along the shores of Portland Bay is of late Pleistocene age. Certain faults occurred in the late Pleistocene or Holocene, and that between Swan Lake and Cape Bridgewater let down a strip of country upon which new dunes began to form. Some of the basaltic capes were too steep for new dunes to form on them. Cape Bridgewater was probably the last of the volcanic islands to be tied to the mainland by the growth of sand dunes on the isthmus.

Latest Uplift of About 10 Feet.

The strongest evidence of the most recent uplift is afforded by the raised beaches at Nelson, Narrawong, and Tyrendarra, raised pebble ridges at Point Danger and Blacknose Point, possible raised shore platforms on some of the headlands, and possible raised marine caves in the Bridgewater district. The combined evidence points to a very Recent elevation of the order of 10 to 15 feet.

The raised beach at Nelson is shown on the geological parish plan of Glenelg, in allotment 14, at an altitude of about 10 feet. Similar deposits occur further east in a ridge protruding into the

Long Swamp. The Narrawong ridge, previously described, consists in its basal part of raised shelly beaches at 15 to 20 feet altitude.

On the eastern extremities of Point Danger and Blacknose Point there are pebble ridges at a height of 10 to 15 feet above the present storm beach pebble deposits.

Many low shore platforms, locally termed "Flat Rocks", occur around the base of the cliffs, particularly in the tuff beds, where they are very level. In the basalt, the shore platforms are irregular in level, due partly to variations in original hardness, and partly to differential erosion. No simple correlation is possible between the rock ledges at various heights on the several capes, though doubtless some of them are genuine raised platforms. Jutson (1939) has recently pointed out the possibility of formation of several levels of platforms with sea level at one height, in connexion with the hypothesis of recent elevation of the coast near Sydney, N.S.W. There are well-developed shore platforms on Lawrence Rock and on Julia Percy Island (McCoy Society, 1937).

Two of the caves on the steep eastern face of Cape Bridgewater are of special interest. One has its floor about 30 feet above sea level. It is high, narrow, and does not penetrate far into the cliff, but is inaccessible; thus it is not known what lies under the storm-tossed boulders on its floor. Griffiths claimed (p. 78) that its position was due to uplift, and probably this interpretation is correct. Another cave, the Water Cave, has its floor well below wave level, and has been found to penetrate several hundred feet, leading into a dry cave. This cave was attributed to later subsidence of a wave-cut cave. It may be pointed out that the tuff beds in the cliff are rather steeply inclined and are predisposed to fracture.

At Vance's Beach, Bridgewater Bay, on the north side of the road skirting Bridgewater Bay, there are two caves, almost filled with sand, in allotment 25, Tarragul. They are cut in dune limestone, and the floors are estimated to be 20 feet above sea level, so they are almost certainly raised wave-cut caves. They are separated from the beach by a foredune.

On the steep eastern bank of the Bridgewater Lakes near Lightbody's is a rock face in which several shallow caves appear. The floors are at 150 feet altitude. Bonwick (1857) thought that they were uplifted marine caves; there are shells, flint scrapers and small bones in the sand on the floor, but the shells are of the large edible kind collected by aborigines, and the bones are of mice dropped from hawks' nests in the roof of the cave. These caves are possibly solution caves exposed by the Swan Lake-Bridgewater fault scarp. The rock is dune limestone.

Numerous small caves at Drik Drik, Puralka, and in Batt's Ridges near Portland are apparently solution caves; it might be possible to obtain evidence of uplift from the fossil bones which are known to occur in some of them. Tindale (1933) who applied this method to the caves at Tantanoola, South Australia, correlated the fauna with the stages of development of the sand ridges of South-east South Australia, the period of formation ranging from Upper Pliocene to Recent.

Although terraces are absent on the larger streams, there are two terraces on Wattle Creek near its mouth, in Henty Park, Portland. The higher is about 30 feet altitude, and is well-marked at the entrance to "Burswood" on the south side of the creek; the lower at 10 to 15 feet occurs throughout Henty Park on the north bank. These terrace formations may, of course, have been due to earlier changes in the stream, or may be caused by uplift.

Conclusions.

Evidence of general uplift of the order of 400 feet is afforded by the widespread dune formations at that altitude. Migration to that height and on such a scale is not admitted. Pleistocene glacial and interglacial periods exerted some control on the rate of dune building by their effect on the sea level; this is reflected in the soil beds separating the dune formations. The most recent elevation was of 10 to 15 feet.

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Appendix.

Estimations of $CaCO_3$ (A. Coulson).

Beach Sands.	$CaCO_3$ *Per cent.*
Mouth of Wattle Creek, Portland	.. 93.00
Dutton Beach, Portland, between tide marks ..	.. 98.75
Pebbly Beach, between tide marks	.. 92.65
Swan Lake Beach, Discovery Bay	.. 75.30
Cape Montesquieu Beach, Discovery Bay	.. 74.75

	$CaCO_3$ Per cent.
Dune Sands, Unconsolidated.	
Dunes 170 feet high, Kentbruck	78.80
Dune 420 feet altitude, near old Mt. Richmond S. School	71.20
Malseed's Lake, wandering dune	79.70
Bridgewater Lakes, between Lightbody's and Kittson's	81.45
Mount Dryden, Cape Bridgewater	69.90
Lake Mombeong (Lake Bung Bung)	77.60
Tyrendarra foredune, 50 feet high	94.05
Mount Kincaid, at 500 feet	56.60
Warrnambool, mouth of Hopkins, foredune 50 feet	92.85
Port Fairy foredune, 50 feet altitude	59.90
Yambuk, foredune at mouth of Eumeralla River	92.60
Dune Rock, Consolidated.	
Bridgewater Lakes, in high caves	98.75
Cape Grant, in cliff face	72.50
Limestone Hill, Cashmore	93.75
400-ft. cliffs overlooking Swan Lake	52.05
Portland Cemetery, quarry near main gate	35.80
Siliceous Sands, from Surface.	
Portland Cemetery	3.22
Blacknose Point, on road	1.15
Rifle Butts, surface	1.00
Rifle Butts cliffs, 20 feet down	5.30
West Gorae, near State School	8.00
Sandy Soil Beds in Dune Limestone.	
Cape Grant, soil bed half-way up cliff	37.75
Cape Nelson, soil bed in cliff	59.90
Cape Montesquieu, soil bed in dune-rock	47.50
Werrikooian Flaggy Limestone.	
Dartmoor Railway Quarry	76.35

Sizing Analyses of Sands (W. R. Jewell, M.Sc.).

Type.	Locality.	On 20 Mesh.	20–40 Mesh.	40–60 Mesh.	60–80 Mesh.	80–100 Mesh.	Through 100 Mesh.
1 (*a*)	Discovery Bay	1·55	4·53	4·21	29·42	57·42	2·87
1 (*b*)	Kentbruck Dunes	1·03	8·92	23·07	56·43	6·45	4·10
1 (*b*)	Bridgewater Lakes, dunes	0·13	1·41	8·11	50·47	20·02	19·86
1 (*b*)	Mt. Dryden, 375′ dune	0·03	0·19	7·12	71·29	11·37	10·00
2 (*a*)	Shelly beach, between tide marks	0·69	0·93	3·22	46·01	29·15	20·00
2 (*b*)	Shelly beach, 100′ foredune	0·04	1·04	4·90	45·81	26·96	21·25
2 (*b*)	Henty beach, foredune	0·01	0·04	0·63	52·73	14·14	32·45
3	Cashmore Heath, surface soil	1·66	28·79	34·39	23·06	6·38	5·72
3	Cape Grant, old soil in cliff	tr.	0·80	47·64	50·57	0·63	0·36
4	Blacknose Point, surface soil	0·06	3·01	14·41	43·87	19·81	18·84

Palaeontological Determinations.

Land Mollusca. In uppermost soil bed, Portland Promontory. (F. Chapman.)

Rhytida gawleri Brazier.
Succinea australis Ferussac.
Laoma cf. minima Cox.

Land Mollusca. In old soil beds, Portland Promontory. (F. Chapman.)
Charopa tamarensis (Petterd).
Charopa spp.
Flammulina sp.

Foraminifera. In uppermost sandy soil, Cape Nelson. (W. J. Parr.)
Uvigerina sp. aff pigmea d'Orbigny.
Discorbis dimidiatus (Jones and Parker).
Discorbis australis Parr.
Discorbis bertheloti (d'Orbigny).
Notorotalia clathrata (Brady).
Cibicides sp. cf. pseudoungerianus (Cushman).
Globigerina bulloides d'Orbigny.
Orbulina universa d'Orbigny.
Elphidium macellum (Fichtel and Moll).
Elphidium imperatrix (Brady).
Quinqueloculina sp.
Triloculina trigonula (Lamarck).
Triloculina insignis (Brady).

Collection from the Oyster Bed, Double Corner, Portland (Miss I. Crespin).

Foraminifera—
Cassidulina subglobosa d'Orb.
Orbulina universa d'Orb.
Polystomellina howchini (Chap. & Parr).
Rotalia beccarii (Linne).
Elphidium imperatrix (Brady).
E. crispum (Linne).

Anthozoa—
Balanophyllia sp.

Polyzoa—
Cellepora fossa Busk.

Pelecypoda—
Anomia tatei Chap. & Sing.
Nuculana crassa (Hinds).
Clausinella subroborata (Tate).
Glycymeris striatularis (Lam).
Corbula coxi Pilsbury.

Gasteropoda—
Bankivia howwitti Tate.
Liopyrga quadricingulata Tate.
Elcurnopsis sp.
Cancellaria sp.
Turritella spp.
Bittium sp.
Nassarius sublirella (Tate).
Natica cf. *hamiltonensis* Tate.

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Explanation of Plate.

Plate XIII.

Fig. 1.—Sand ridge running east and west, oblique to coast, Discovery Bay, two miles west of Swan Lake.

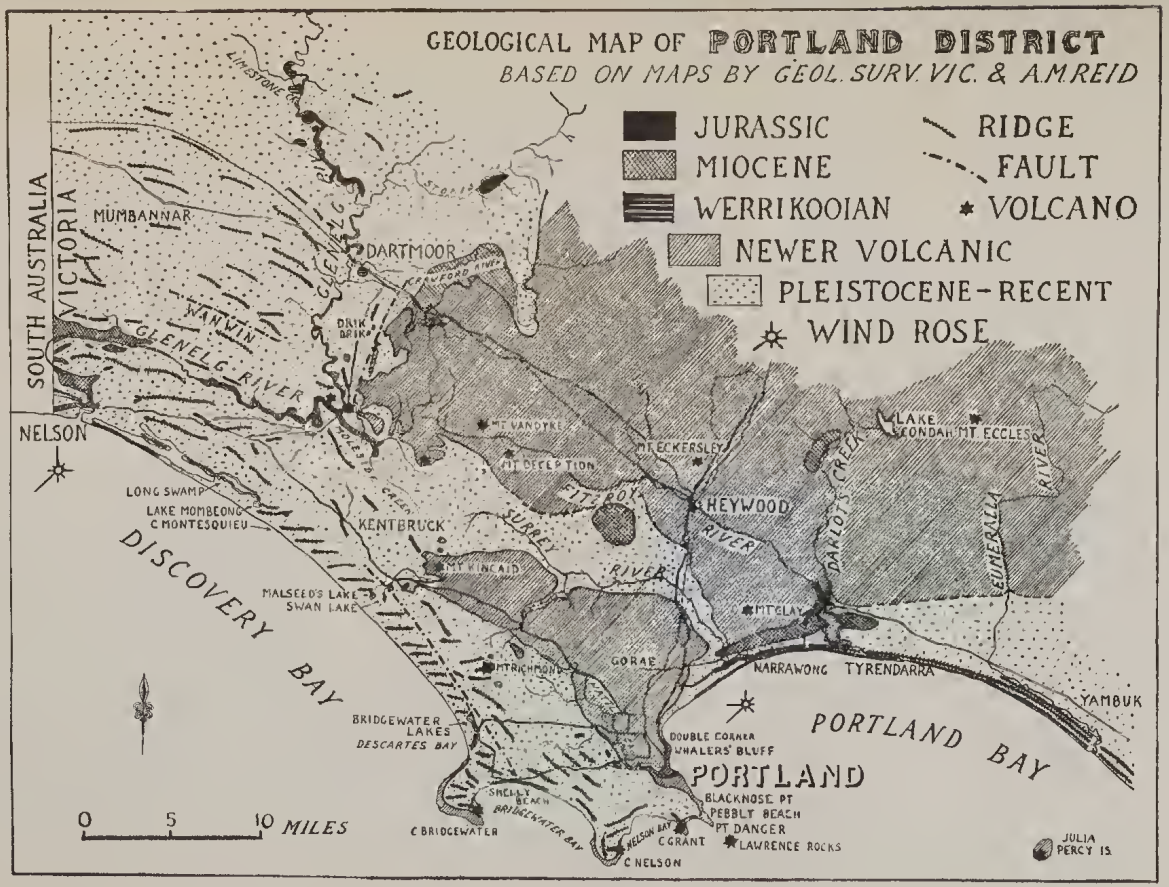
Fig. 2.—Incipient compaction of sand in layers in a foredune, Discovery Bay, seaward side of Bridgewater Lakes.

Fig. 3.—Lee slope of dune with encroachment of dry sand (white) over-running wet sand (dark), Discovery Bay north of Bridgewater.


1


2


3


GEOLOGICAL MAP OF PORTLAND DISTRICT
BASED ON MAPS BY GEOL. SURV. VIC. & A.M.REID
JURASSIC
MIOCENE
WERRIKOOIAN
NEWER VOLCANIC
PLEISTOCENE-RECENT
RIDGE
FAULT
VOLCANO
WIND ROSE
SOUTH AUSTRALIA
VICTORIA
MUMBANNAR
DARTMOOR
WANWIN
GLENELG RIVER
NELSON
LONG SWAMP
LAKE MOMBEONG
C MONTESQUIEU
KENTBRUCK
MT KINCAID
MALSEED'S LAKE
SWAN LAKE
DISCOVERY BAY
BRIDGEWATER LAKES
DESCARTES BAY
C BRIDGEWATER
MT VANDYKE
MT DECEPTION
MT ECKERSLEY
MT CLAY
HEYWOOD
SURREY RIVER
LAKE CONDAH
MT ECCLES
DARLOTS CREEK
EUMERALLA RIVER
GORAE
NARRAWONG
TYRENDARRA
YAMBUK
TRICHMOND
DOUBLE CORNER
WHALERS' BLUFF
PORTLAND
PORTLAND BAY
BLACKNOSE PT
PEBBLE BEACH
PT DANGER
C GRANT
LAWRENCE ROCKS
C NELSON
JULIA PERCY IS.
0 5 10 MILES